A Worldwide Organization to Secure Earth-Related Parameters for Deep Space Missions

H. F. Fliegel
Tracking and Orbit Determination Section

A global express service to obtain timing and polar motion parameters for deep space mission support has been organized through the Bureau International de l'Heure. The results are incorporated into a daily operation. This article outlines what the new sources of data are, what procedures are used to reduce the data, and what software is available to the user.

I. Introduction

The need for increased accuracy in determining DSN coordinates to support *Mariner* Mars 1971 and future missions has made two major changes necessary at JPL to obtain timing and polar motion parameters. This article outlines what the new sources of data are, what procedures are used to reduce them, and what software is available to the user. The timing parameters and their importance were explained by Trask and Muller (Ref. 1). An introduction to the whole subject of timing and its use in spacecraft orbit determination was given by Moyer (Ref. 2). A similar introduction to polar motion was given by Muller (Ref. 3).

The first major change from the procedure used to support *Mariner* Mars 1969 is in securing astronomical data from a worldwide network of observatories rather than from the US Naval Observatory alone. The primary reason for this change was to obtain polar motion values with standard deviation not exceeding 0.7 meters, according to our committed error budget. Polar position cannot be obtained by US observatories alone. The Bureau International de l'Heure (BIH) has for many years collected, reduced, and published polar motion and timing data from cooperating national time services throughout the world. However, the most recent published data is from 40 to 70 days old, and errors due to extrapolating such data are often 1 to 3 meters. Beginning in 1971, JPL has sponsored a contract for BIH to obtain time and latitude data from at least 12 cooperating observatories by teletype, as soon as obtained, to provide the world's first rapid time and polar motion service. A secondary, but quite important, benefit of this service is to reduce the random error in UT1 to less than 5 ms. Systematic errors of any one observatory tend to average out, bad weather in any one part of the world does not seriously affect the service, and real-time measurements of polar motion improve the accuracy of UT1 which is computed therefrom.

The second major change in JPL procedure has been to replace the former TPOLY computer program with the THALES–PLATO systems and a variety of smaller supporting programs. (For a description of the TPOLY program, see Ref. 4.) With measurements arriving from 12 or more observatories and not from 2 only, a great deal more is required in preliminary error analysis and screening of the data than formerly. Furthermore, since timing parameter decks are being generated for the mission virtually on a real-time basis and not long in advance, an error-free system, coupling a flexible output format with numerous internal and external checks for accuracy, becomes essential.

This article discusses the organization of the rapid time and polar motion service of the BIH and describes the types of information BIH supplies, the schedule of delivery, and the format of data transmission. The concluding section of this article gives a preliminary sketch of how well the service seems to perform. A more complete analysis will appear after the *Mariner* Mars 1971 mission.

II. The BIH Rapid Time and Polar Motion Service

The Bureau International de l'Heure (BIH) is the agency sponsored by the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG) to collate, reduce, and publish timing data from all cooperating national time services throughout the world, and by means of such data to secure scientifically accurate and internationally accepted standards of time. BIH is supported by UNESCO. By resolution of the IAU, BIH uses its astronomical data to solve both for UT1 and for the instantaneous coordinates X and Y of the terrestrial pole, which three quantities specify the orientation of the Earth in space. Published final values of these quantities appear in BIH Circular D about one month after observation. However, since the causes of the variation of the Earth's rotation are many and are not completely known, the parameters of that rotation, UT1, X, Y, cannot be predicted accurately in advance, and the time-lag between observation and publication was a vexing source of error to many users. In particular, JPL could not use Circular D information for real-time mission operations. Therefore, Dr. Bernard Guinot, the director of BIH, decided to enlist the cooperation of a limited number of highly accurate time and latitude observatories to form the world's first rapid time and polar motion service. (The strategy is somewhat similar to that of an earlier effort called the Rapid Latitude Service, but the present service embraces time and polar motion in a single solution.)

One must distinguish between the astronomical service itself, which is exclusively a BIH function currently financed by JPL, and the use of the service to provide machine-readable timing and polar motion parameter decks suitable for space missions, which is a joint effort between BIH and JPL. We will speak of the former as the BIH Rapid Service, and of the latter as the JPL–BIH Operation.

The BIH Rapid Service hinges on the cooperation of a select list of observatories. Data from 76 observatories were included in the BIH Circular D solutions for time and/or latitude in 1969 (the year of the *Mariner 6* and *7* missions), but the observatories were far from equal in weight. Weights in the BIH system are chosen to be the squares of integers, and, in the timing solutions for the year 1969, 10 stations had weight 49, 10 had weight 25, 6 had weight 16, and the sum of the weights of all the rest was only 114. These weights, of course, are inversely proportional to the squares of the measured standard deviations of the data; they are far higher for modern instruments observing stars of well-determined positions than for either the older types of visual instruments or for new observatories just beginning to establish their catalogs. Thus, the 10 observatories of weight 49 contribute more than half the total weight of the final solution for time, and a similar situation obtains for latitude. Therefore, an efficient and reasonably accurate rapid service can be organized by obtaining data by teletype from only those observatories of high weight. Furthermore, since the systematic errors of these observatories persist from year to year, they can be measured from the final solution for previous months and corrected in advance. Thus, the accuracy of the BIH Rapid Service can be made even greater than the weights of the contributing observatories alone would indicate. Such, then, is the strategy of the Service: first, to select for participation well-established observatories; and, second, to apply systematic corrections based on past performance. Note carefully that even observatories which do not contribute directly to the Rapid Service are important to it, for they help determine the systematic corrections to those which do.

The list of observatories participating in the BIH Rapid Service as of August 1971 is given in Table 1.

BIH reduces the data from the observatories contributing to its Rapid Service by the same procedures it uses to prepare Circular D or the *Rapport Annuel*; thus, all BIH publications are on the same system. Rapid Service reductions are made at 3.5-day intervals, rather than at the 5-day intervals used for Circular D. Following the most recent data as closely as possible, BIH computes each week straight line segments—initial values and rates—which characterize the behavior of X, Y, and UT1 during that week, and teletypes them to its Rapid Service subscribers (currently, JPL). It is not practical for BIH to force the values at the beginning of one week to agree with the values at the end of the previous week, since raw time and latitude data are notoriously noisy, and frequently an apparent upward trend one week is shown by the following week's data to have been an illusion. Thus, the sequence of straight line segments are not joined at the ends; they constitute a discontinuous function. JPL requires timing and polar motion functions more amenable to extensive machine calculation, and JPL procedures are described in the following section.

III. The JPL–BIH Operation: The THALES–PLATO Systems

The special requirements on timing and polar motion for deep space mission support are as follows:

(1) The quantities UT1, X, and Y should be specified in the form of functions, readily computable, continuous in the first derivative.

(2) For the *Mariner* Mars 1971 mission, the standard deviation of the computed X and Y of polar position should not exceed 0.7 meters, and that of timing should not exceed 4 ms.

(3) Parameters should be predicted and supplied as far in advance as possible, but it is especially important that unexpected changes in the Earth's rotation be reported as rapidly as possible.

(4) Since the timing and polar motion routines form only a tiny part of the orbit determination program, and since no one person can have an intuitive feel for all the factors entering into a given day's solution for spacecraft position, it is essential that operations be fully automatic, with high redundancy and numerous safeguards to avoid error.

Practically, the data processing required divides conveniently into two major tasks. First, one must form the best real-time estimates of X, Y, and UT1 and their rates of change, the rates being especially important because of the need to predict ahead for at least a few days. In this first task one must also estimate the accuracy of the real-time solutions, evaluating the quality of the optical observations as it changes with weather, season, and unknown factors. Second, one must represent the sequence of such estimates formed week after week by some mathematical function, and supply parameters in machine-readable form which define that function for such programs as SATODP (Satellite Orbit Determination Program). Other minor tasks—minor in the sense of requiring less software, but important to guaranteeing mission success—are checking final output decks for mathematical consistency and against punch errors, and providing contingency procedures for use against systems failures, loss of one computer due to power failure, earthquake, or other causes. The first major task is performed by program THALES, and the second by PLATO. Between those two programs stands the cognizant engineer, who must examine the residuals of the optical observations supplied by BIH and certify THALES output before passing it on to PLATO. The relationship of THALES to PLATO, and of both to the BIH Rapid Service and to other programs, is diagrammed in Fig. 1. We now describe the programs.

THALES (Time Handling And Latitude Evaluation System) reduces raw astronomical measurements of time and latitude to X, Y, and UT1. For this purpose, BIH sends JPL copies of the data sheets submitted by each observatory contributing to the Rapid Service. THALES computes the check sums which verify that the data has been teletyped properly, computes X, Y, and UT1 for each batch of data corrected to whatever epoch the operator supplies by NAMELIST (a Fortran term) input, and lists the residuals of each observation from the mean solution, computing the largest residual, the mean residual, and the standard deviation for each observatory.

PLATO (PLATform Observables) accepts X, Y, and UT1 input from any source (currently, from THALES), fits through the data any of a variety of orthonormal function series (Fourier, Chebyshev) or splined cubics, at the operator's discretion, and produces the final output deck which is used by TIMPOL (see below) in the SATODP and other programs for mission support.

CYNIC (Checklisting Yes–No Indicator of Consistency) is used in the certification of PLATO output decks. CYNIC checks the format of the PLATO deck against missing parentheses, cards out of order, and the like; it also checks seconds past 1950, A.1 − UT1, and A.1 − UTC against the civil date of the label. Such seeming redundancy was found necessary to screen out operator error and possible system errors in the running of the fairly intricate program PLATO.

STOIC (Standby Timing Operation In Contingencies) is a backup program that can generate an output deck in the PLATO format directly from THALES output in case the PLATO system through some accident becomes inoperative. It is currently under development.

TIMPOL (TIMe and POLe) is the subroutine actually called in the orbital determination programs SATODP and DPTRAJ and other programs which makes use of the data read in from the PLATO output deck to compute parameters at the instant specified by the user.

IV. Level of Performance—A Preliminary Sketch

Since predictions must be made a few days in advance even when using the Rapid Service, and in order to average out the random errors in the data for each given week, THALES fits a smooth curve each week through the data for the past eight weeks and extrapolates it forward. For polar motion, an Archimedean spiral arc is fit, centered on the point $X = 0.00$, $Y = 0.25$, which is the approximate center of polar wandering in recent years. To timing data, a straight line is fit to UT2. This procedure gives two measures of the consistency of the reduced data. One may calculate the mean standard deviation of a given week's data from the eight-week curve. Averaging since the inception of the service, we obtain

$$\sigma_X = 0.021 \text{ arc sec} = 0.65 \text{ meters}$$

$$\sigma_Y = 0.019 \text{ arc sec} = 0.58 \text{ meters}$$

$$\sigma_T = 2.7 \text{ milliseconds}$$

We may also compare different eight-week curves, and compute the standard deviations of the values of X, Y, and UT1 calculated for a given date. For a typical date, we obtain

$$\sigma_X = 0.0064 \text{ arc sec} = 0.20 \text{ meters}$$

$$\sigma_Y = 0.0086 \text{ arc sec} = 0.27 \text{ meters}$$

$$\sigma_T = 1.4 \text{ milliseconds}$$

The first set of figures measures how well the model fits the data, and the second set measures how well X, Y, and UT1 can be obtained if one believes the model. Clearly, THALES reduces the data consistently and uses a model that fits the data well over eight-week intervals. Furthermore, the model is useful for prediction. The error in predicting UT1 35 days in advance of the *Apollo 15* launch was 6 milliseconds, and declined linearly as the awaited day approached.

However, "if all men went mad after the same fashion, they might agree one with another well enough.[1]" Three facts remind us that the measures of consistency given above are perhaps a factor of 3 more optimistic than the true accuracy of the operation:

(1) The X-coordinate of polar motion from THALES agrees rather well with that from BIH, but the Y-coordinate has been consistently 2 meters too small. Similar discrepancies exist between International Latitude Service (ILS), BIH, and the US Naval Weapons Laboratory solutions (see Ref. 5). We are currently using an empirical correction to make PLATO agree with BIH.

(2) Various observatories contributing to the BIH Rapid Service display short-term errors consistent over eight weeks but different from previous years. For example, Richmond has consistently reported UT1 from 10 to 20 milliseconds higher than Washington during the spring and summer of this year.

(3) In past years, BIH UT2 has remained nearly linear with constant slope for weeks or months at a time, only to change its slope suddenly to a new value. Roughly 10 such events have occurred in the past six years, most recently in mid-March of 1971. The UT2 fit over eight weeks, described above, will display high precision only until the next such event, during which a much shorter averaging span must be used.

We believe, therefore, that the Tracking System Analytical Calibration (TSAC) figures of merit adopted for *Mariner* Mars 1971 ($\sigma = 0.7$ meters in X and Y and $\sigma = 4$ milliseconds in UT1) are a realistic estimate of the quality of the present JPL–BIH Operation.

V. Summary

(1) The BIH Rapid Service is now supplying by teletype time and polar motion values obtained from

[1]Francis Bacon, *Novum Organum*, Aphorism XXVII.

not less than 12 observatories distributed around the globe, virtually on a real-time basis.

(2) JPL is making its own reduction of raw astronomical data, which BIH supplies in addition to its own Rapid Service. The data processing is divided into two major programs: THALES, to solve for X, Y, and UT1 from the raw data; and PLATO, to represent X, Y, and UT1 in machine-readable form.

(3) The existing service satisfies the TSAC requirements for *Mariner* Mars 1971, but probably could not satisfy requirements much more stringent. We believe that we are close to reaching the ultimate accuracy obtainable from conventional astronomical measurements.

References

1. Trask, D. W., and Muller, P. M., "Timing: DSIF Two-Way Doppler Inherent Accuracy Limitations," in *The Deep Space Network*, Space Programs Summary 37-39, Vol. III, pp. 7–16. Jet Propulsion Laboratory, Pasadena, Calif., May 31, 1966.
2. Moyer, T. D., *Mathematical Formulation of the Double-Precision Orbit Determination Program (DPODP)*, Technical Report 32-1527. Jet Propulsion Laboratory, Pasadena, Calif., May 15, 1971.
3. Muller, P. M., "Polar Motion and DSN Station Locations," in *The Deep Space Network*, Space Programs Summary 37-45, Vol. III, pp. 10–14. Jet Propulsion Laboratory, Pasadena, Calif., May 31, 1967.
4. Muller, P. M., and Chao, C. C., "New Timing Polynomial Program and Data," in *The Deep Space Network*, Space Programs Summary 37-57, Vol. II, pp. 42–51. Jet Propulsion Laboratory, Pasadena, Calif., May 31, 1969.
5. Chao, C. C., and Fliegel, H. F., "Polar Motion: Doppler Determination Using Satellites Compared to Optical Results," in *The Deep Space Network*, Space Programs Summary 37-66, Vol. II, pp. 23–26. Jet Propulsion Laboratory, Pasadena, Calif., Nov. 30, 1970.

Table 1. Observatories participating in BIH Rapid Service

Observatory	Location	BIH code	Instrument
Besançon	France	BS	Astrolabe
Calgary	Alberta, Canada	CL	PZT[a]
Herstmonceux	Sussex, England	G	PZT
Hamburg	Germany	H	PZT
Mount Stromlo	Canberra, Australia	MS	PZT
Mizusawa	Japan	MZP	PZT
Ottawa	Ontario, Canada	O	PZT
Paris	France	PA	Astrolabe
Paris North	France	PAN	Astrolabe
Richmond	Florida, USA	RCP	PZT
Santiago	Chile	SC	Astrolabe
San Fernando	Spain	SFA	Astrolabe
Tokyo	Japan	TO	PZT
Washington	DC, USA	W	PZT

[a]PZT = photographic zenith tube.

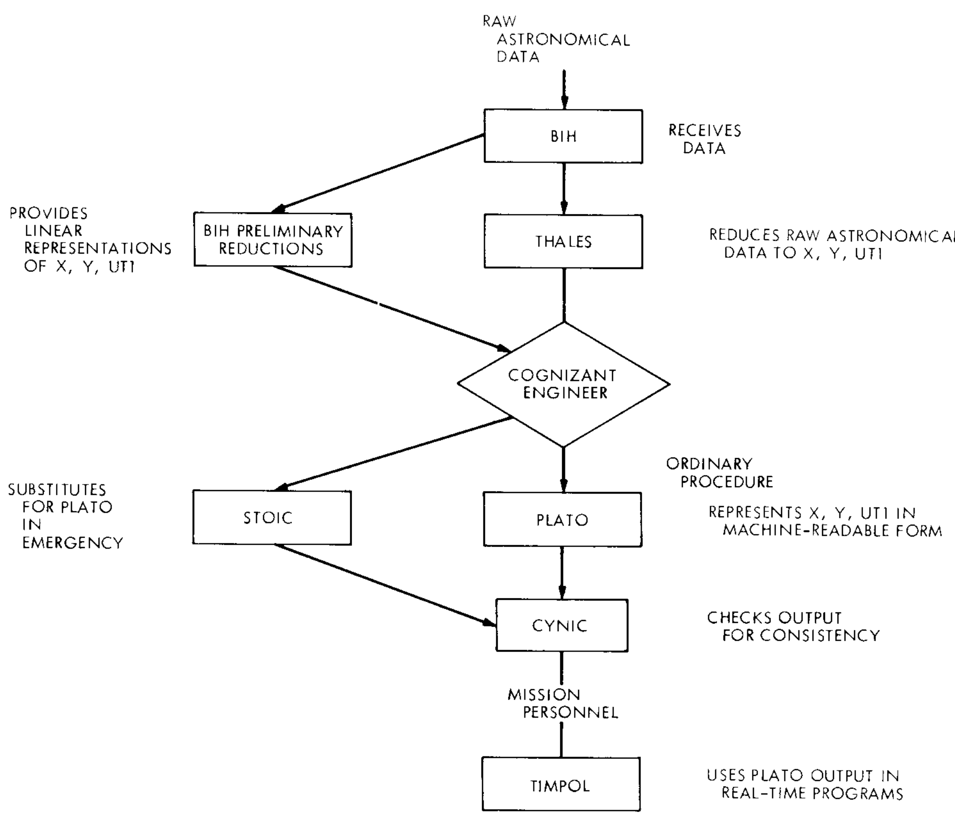

Fig. 1. Interrelationships between JPL–BIH operations

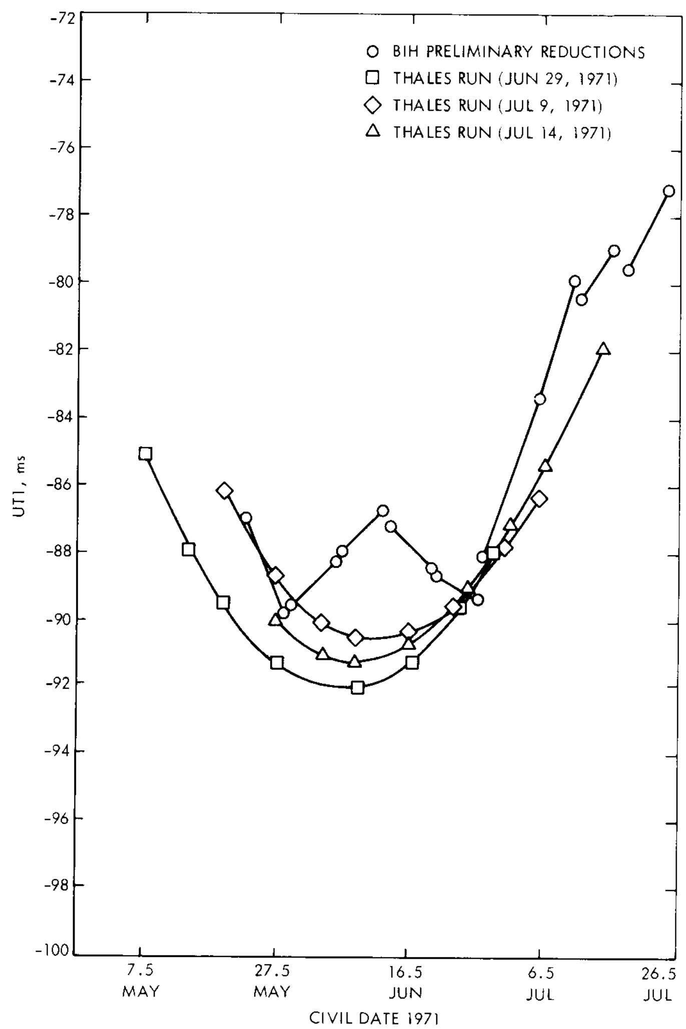

Fig. 2. THALES and BIH representations of UT1